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INVESTIGATION OF CLOUD AND PRECIPITATION
PHYSICS BY RADAR

J. S. Marshall

McGill University

Prepared for:

Air Force Cambridge Research Laboratories

1 March 1972

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INVESTIGATION OF CLOUD AND PRECIPITATION

PHYSICS BY RADAR

by

J. S. Marshall

Stormy Weather Group
McGill University
Montreal, Canada

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13. ABSTRACT Significant developments in instrumentation directed toward the optimum use of radar in investigations of cloud and precipitation physics were accomplished. A new technique in film display of radar information provides intensity maps in conformal map form. This display, called AZLOR, complements the standard PPI display with detail and conformity to the true pattern in small areas. The technique of pulse compression was devised and employed in selected weather situations. This technique has the advantage of permitting increase in sensitivity without compromising the resolution of the radar. A body of microwave attenuation statistics was accumulated from AZLOR records of severe storms. Data were accumulated and analyzed to relate precipitation seen by radar to cloud seen by photography. Radio-located lightning flashes were related to precipitation by radar. A new technique was explored to extrapolate radar precipitation measurements to the surface for comparison with rain gauges. Other research studies include: short term forecasting using Height Plus Plan Indicator records; peak reading as signal processing technique; interrelationship of showers and contiguous rain; and measurement of snowfall radar.		

THE MCGILL RADAR WEATHER OBSERVATORY

Final Report to AFCRL
Contract F19628-69-C-0107

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McGill Radar Weather Observatory
1 March 1972

Details of illustrations in
this document may be better
studied on microfiche

The Stormy Weather Research Group

The group's activities have always been centred on the McGill Weather Radar. Since 1956, however, the group's attention has been shared, and is now shared about equally, between the McGill Radar and the Alberta Hail Studies. Members of the group, and their principal involvement, are as follows:

<u>McGill Radar</u>	<u>Alberta Hail</u>
J.S. Marshall ⁺	W. Hitschfeld
E.J. Stansbury	(J.S. Marshall) ⁺
E. Ballantyne	R.R. Rogers ⁺
G.L. Austin	H. Leighton
G. Drufuca	N. Cherry

While the two columns indicate a clear division of responsibilities (with "management" indicated by asterisks), all members of the group and their graduate students have strong bonds of common interest.

Prof. Marshall now has very nearly full time available for research, primarily radar display development and secondarily storm dynamics.

Dean Stansbury concerns himself with radio location of lightning, with a view to relating lightning activity to the radar record of precipitation. As Dean of Science, he has less than the average professor's time to devote to research.

Mr. Ballantyne is full-time engineer-in-charge at the McGill Radar Weather Observatory, where he has a staff of one engineering assistant (Mr. Abnash Singh) and two senior radar technicians (Messrs. Martin Claassen and Philipp Seidenfuss). He shared the task of establishing the radar with Dr. R.W. Fetter, who is now with David Atlas at Chicago. Display development is shared between Marshall and Ballantyne; the latter did all the work, in that he developed the circuits and with his staff built the equipment.

Dr. G.L. Austin is assistant professor of physics and has about half his time available for research. A native of England and a Cambridge graduate, he had experience in ionospheric research in New Zealand before coming to McGill and redirecting his interest to the troposphere. Apart from his involvement in the radar, he has taken over our cloud photogrammetry.

Dr. G. Drufuca is an electrical engineer from Milan who came to us as a research associate in 1970. His primary involvement is in obtaining from radar records at a non-attenuating wavelength statistics on the attenuation that would be experienced on a higher-frequency microwave communications link.

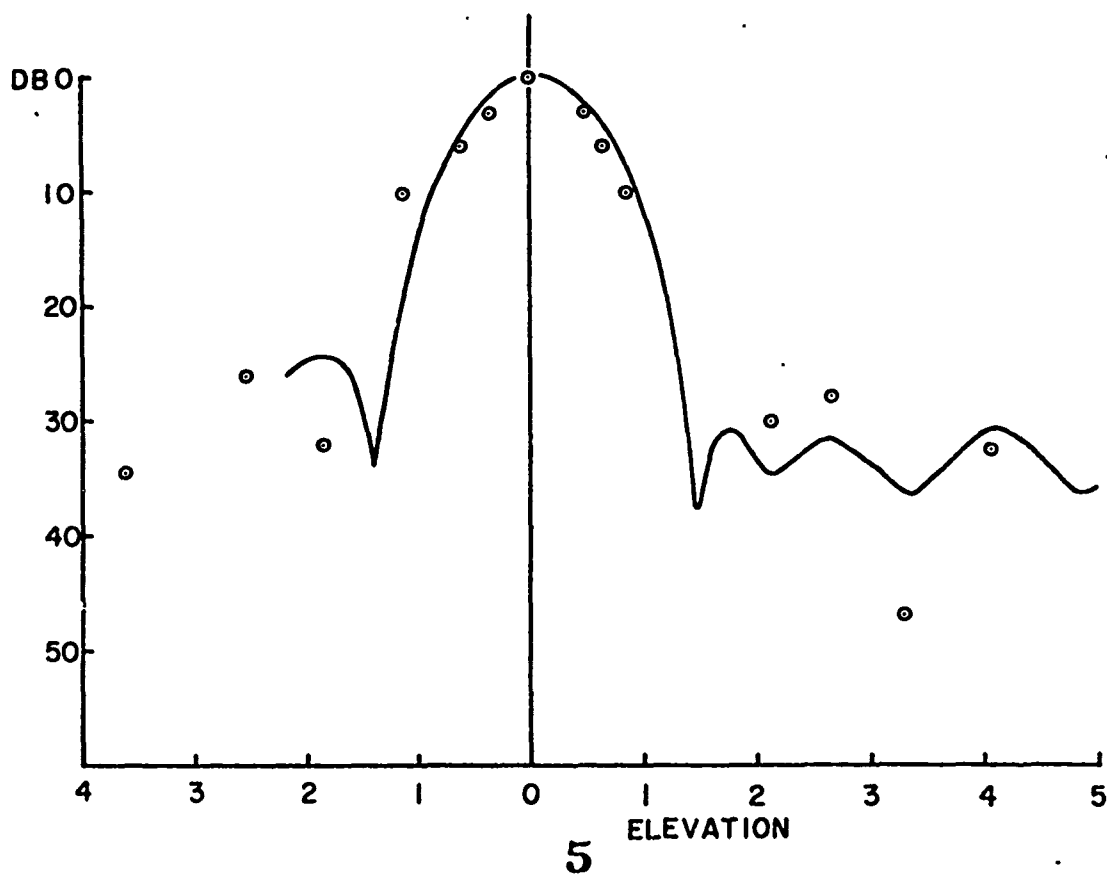
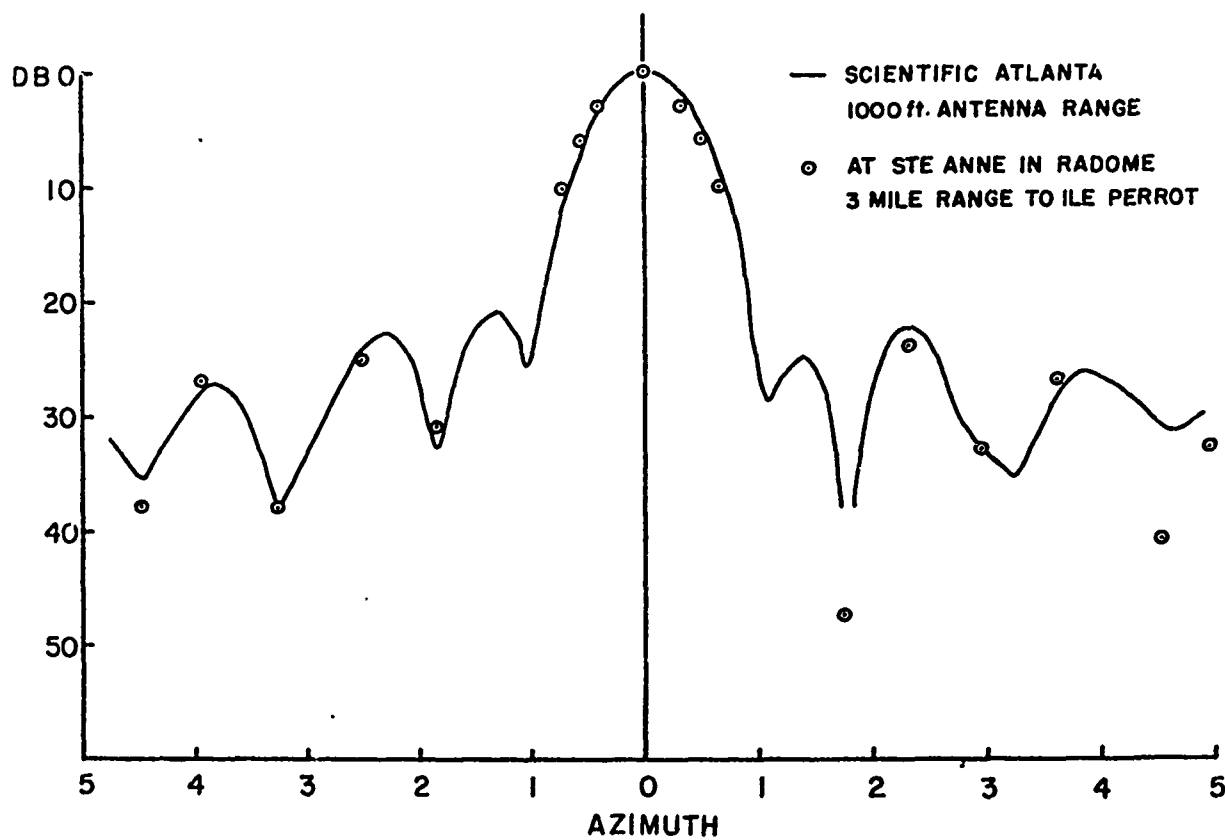
Turning to group members whose predominant involvement is in hail research: Dean Hitschfeld is a world leader in hail research. As Dean of Graduate Studies and Research, he has less than one quarter of his time available for research; he has turned over the management of our Alberta Hail undertakings to Rogers and Marshall, so that the available time will go to genuine research. Prof. Rogers was, like Dr. Drufuca, interested in attenuation statistics, but has been attracted to hail research by the availability in Alberta of an antenna uniquely equipped for polarization experiments. Dr. Leighton is a teaching fellow in the process of converting himself from nuclear physicist to meteorologist. Dr. Cherry, another teaching fellow, is a young New Zealand physicist who studied lee waves in New Zealand and who is well suited to move in rapidly on the problems of hail research.

The group employs full time a photographic technician, a draughtsman and two secretaries.

The McGill Radar Weather Observatory

Capital investment: a grant from the National Research Council of Canada paid for the 30-foot antenna and pedestal, radome and tower. It also paid for the modification of an 8.6-cm magnetron radar, but this was disallowed by the licensing authority. In this situation, efforts to obtain a radar with transmitting klystrons were renewed, and the FPS-18 was obtained on loan through AFCRL. The observatory building was paid for by a private and anonymous benefaction to McGill University.

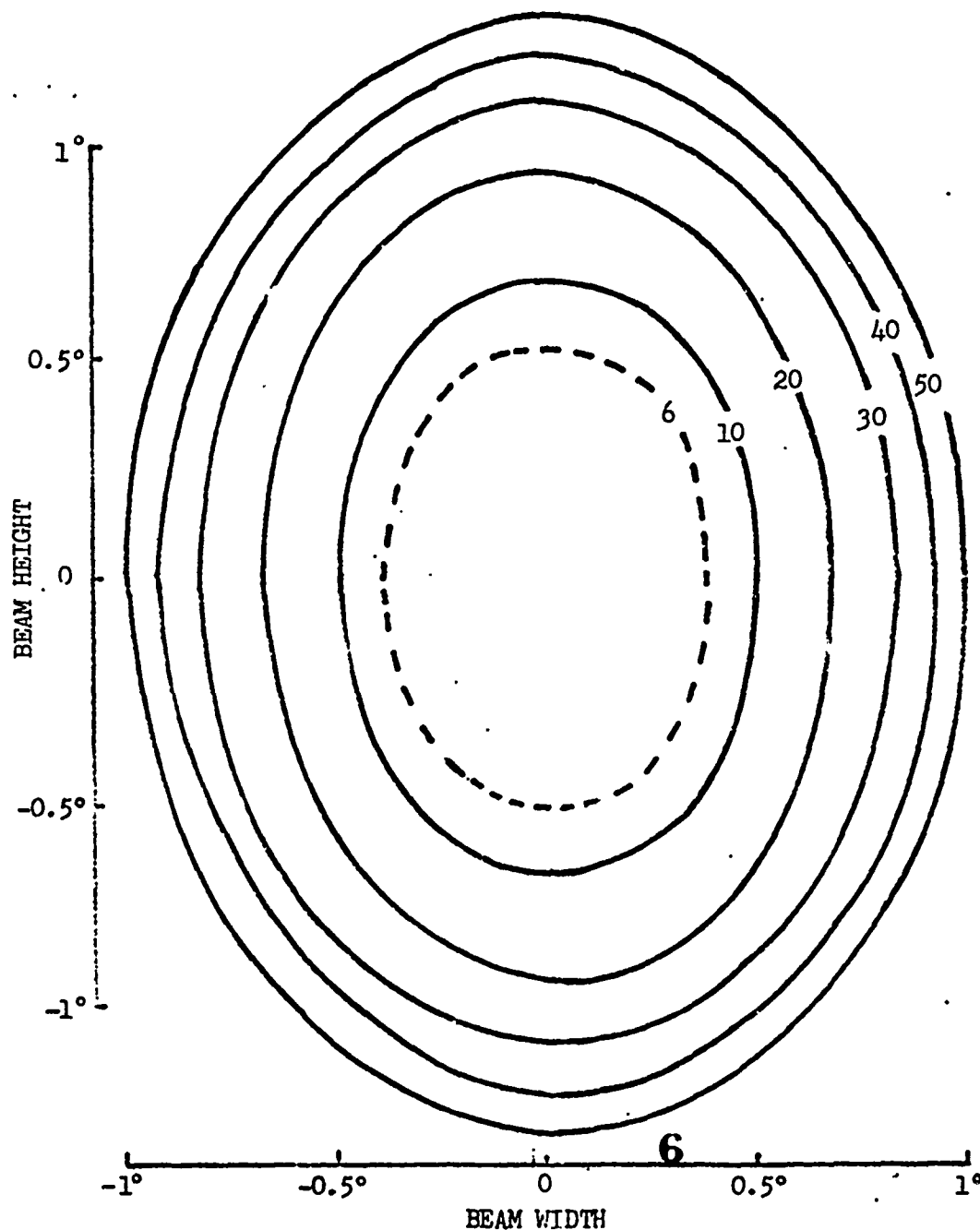
Sources of continuing support, additional to AFCRL in loaning us the FPS-18, are the National Research Council of Canada, the Atmospheric Environment Service of Environment Canada, and the Communications Research Centre of the Canadian Department of Communications.



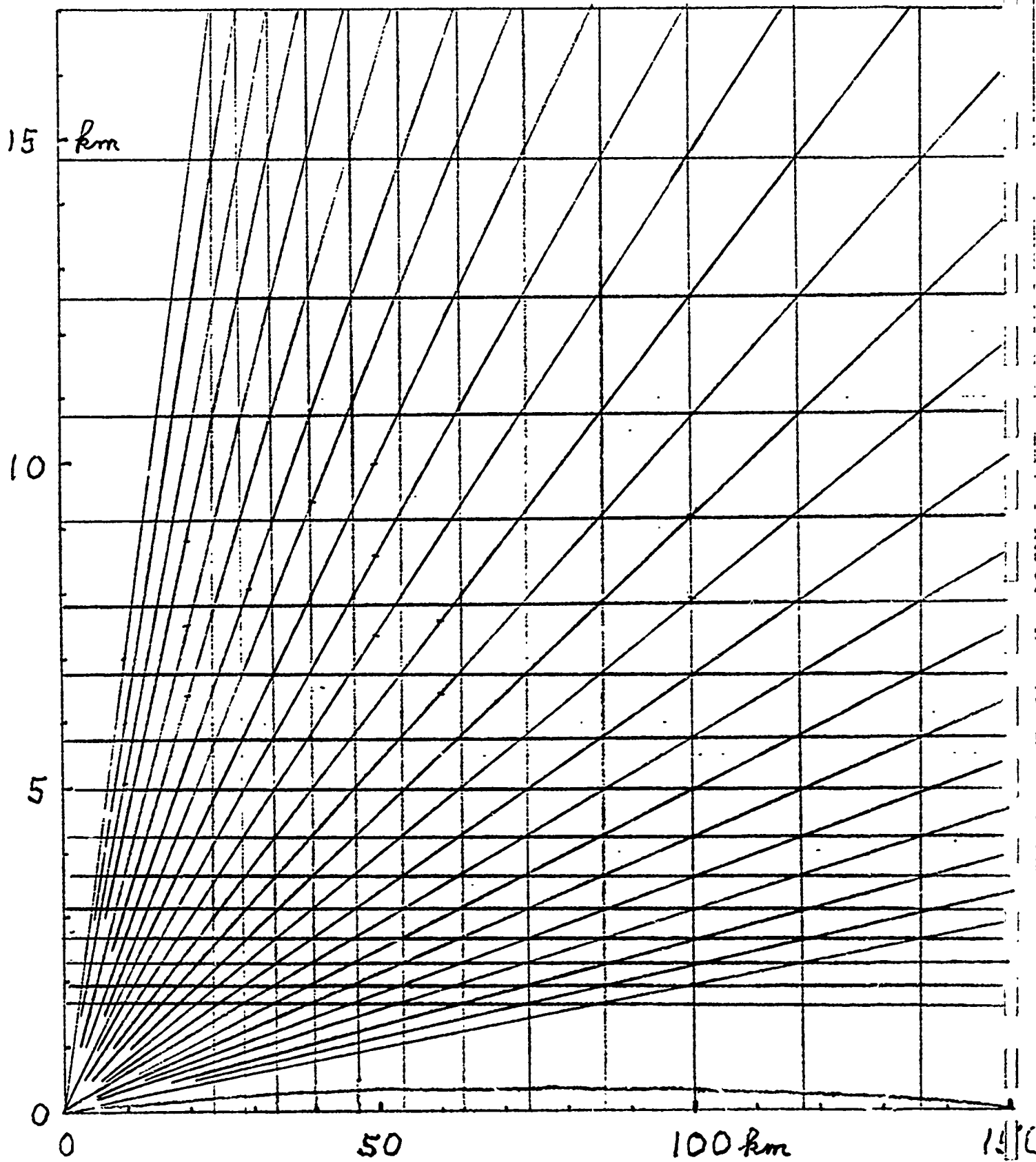
McGill Weather Radar Observatory
antenna beam pattern, one way.

Antenna, Radome, Beam Pattern

The antenna pedestal is mounted on a platform 85 ft above grade; antenna and pedestal are protected by a geodesic radome. With a reflector of diameter 30 ft, the antenna gives a beam of angular extent 0.8° in azimuth by 1.0° in elevation. These dimensions are just to level 6 dB (radar) below peak; for weather radar it should be borne in mind that width to -25 dB is twice as great. Sidelobes are below -40 dB and generally better than -50 dB (radar).



McGill
Weather
Radar
Observatory
antenna beam
pattern
in cross
section.
Radar or
2-way values
are given
in decibels.



GP antenna program, ratio 7/6.

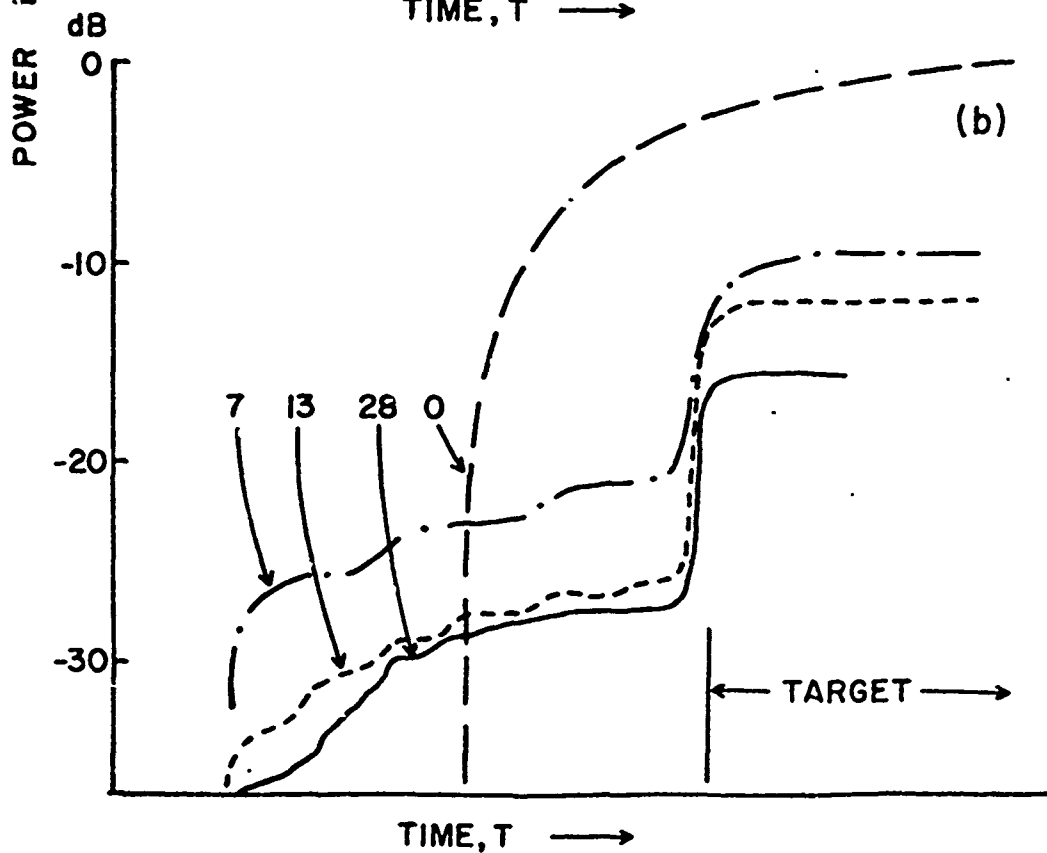
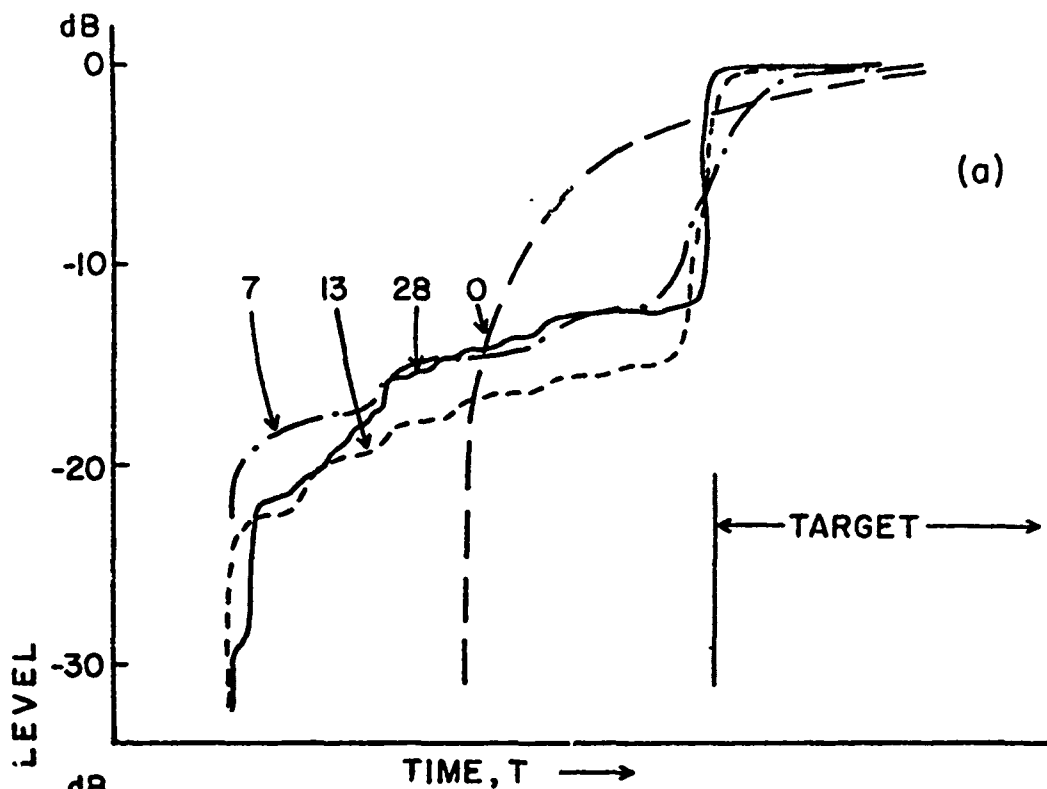
FASE (Fast azimuth slow elevation) Antenna Program

Since the introduction of CAPPI twenty years ago, the antenna has been programmed to rotate steadily in azimuth, with successive rotations at progressively higher angles of elevation. The present rate in azimuth is six revolutions per minute, or $\pi/5$ rad s^{-1} . The low figure of 60 s^{-1} is used for the pulse repetition frequency, so that the axes of successive beams are separated by $\pi/300$ radian, or half a beamwidth at level 15 dB below peak.

The elevation angle is held constant through one rotation in azimuth, then raised incrementally during a quiet sector of $2\pi/15$ radians of azimuth, then again held constant for one rotation.

We are now using a GP (geometric progression) program: the values of $\tan \phi$ (where ϕ is elevation) increase in geometric progression, up to a maximum of about 35° for ϕ . The whole program takes 5 minutes, and is repeated every 5 minutes.

The base line from which ϕ is measured is depressed by 0.5° below the horizon. This depressed base line, when rotated about a vertical axis, sweeps out a conical approximation to the curved surface of the earth.



Power returned from an extended target for a pulse of constant duration compressed by factors 0, 7, 13 and 28. (a) shows relative power. (b) shows signal-to-noise performance.

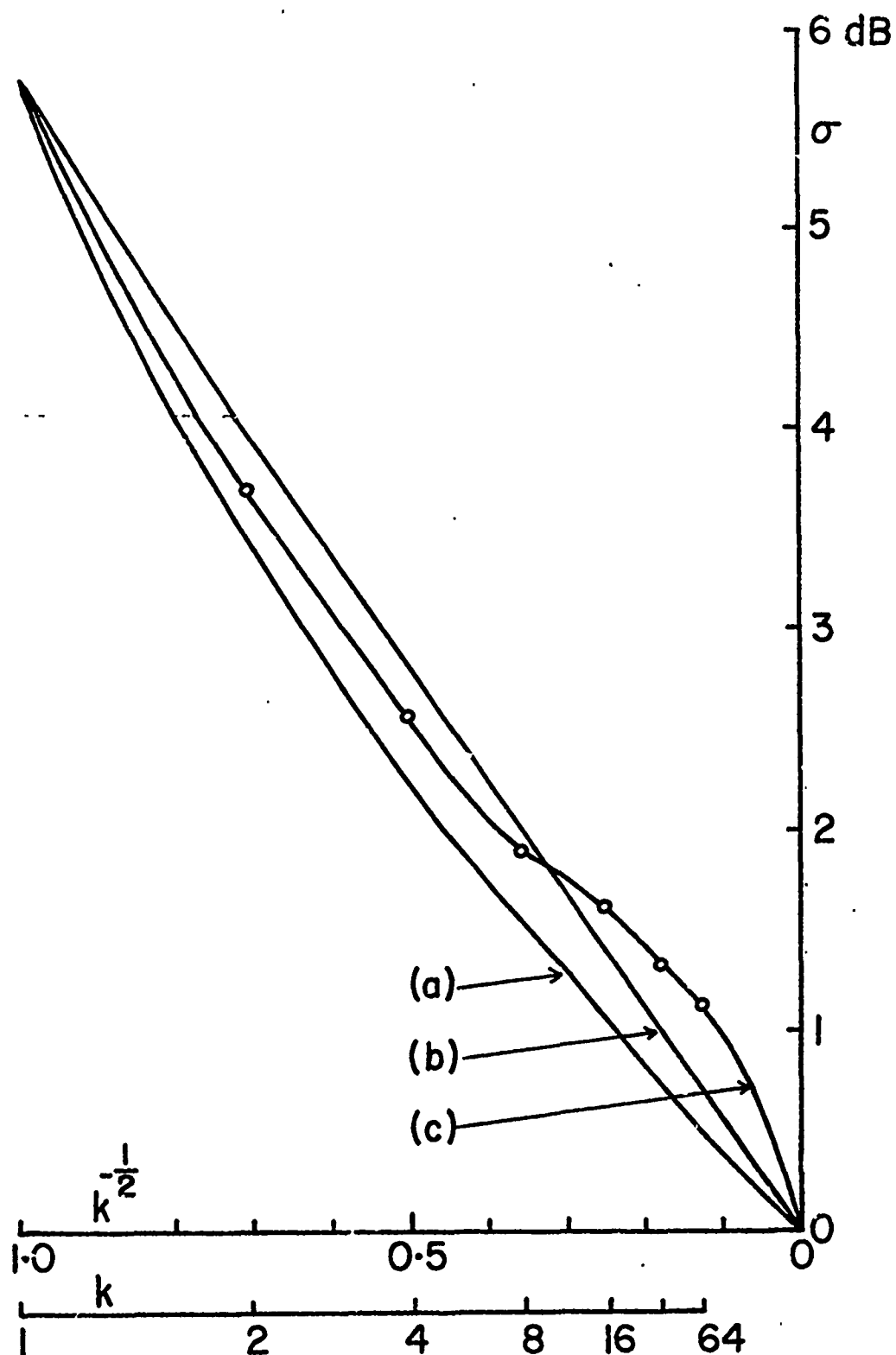
Pulse Compression

In the compromise between resolution (in range) and sensitivity, reduction of the pulse duration by a factor a , and the concomitant widening of the bandwidth by the same factor, reduce sensitivity by $20 \log a$ dB. If pulse compression is used, however, compression by factor b reduces sensitivity by only $10 \log b$ dB, i.e. by only half as many decibels.

The FPS-18 normally has a pulse duration of 1 μ sec. We have installed a new pulse transformer, giving a pulse duration of 4 μ sec. Used with narrower bandwidth and without pulse compression, the change reduces resolution by factor 4 and increases sensitivity by $20 \log 4 = 12$ dB. We have also installed phase-coded pulse compression, by factor 13 or 28. That improves the resolution by factor 13 (overall $13/4 \approx 3$) and reduces sensitivity by 11.4 dB (overall $12 - 11.4 \approx 0$). If that improvement in resolution had been achieved by simply shortening the pulse, the cost in sensitivity would have been $20 \log 3 \approx 10$ dB. Achieved by pulse compression, the cost in sensitivity is zero. However, the improvement in resolution has limitations, in the form of "range sidelobes" down about 15 dB from peak. For the "extensive" targets of weather radar, these sidelobes form a sort of shelf, down about 15 dB and extending out by the width of the uncompressed pulse: 4 μ sec or 0.6 km.

There is a real advantage to us in having a 4 μ sec pulse: the sensitivity increase of 12 dB was needed, especially for snow. Because we combine data in range to reduce fluctuations, the pulse compression affords an advantage too, but the side effects of range sidelobes are hard to evaluate.

REFERENCE: Austin, G.L. and R.W. Fetter, 1972: Pulse compression for meteorological radars. Sci. Rept. MW-70, Stormy Weather Group, McGill Univ., Montreal, 24 pp.



Standard deviation (σ) of probability distribution of target intensity level, when k independent data are combined by (a) averaging intensities, (b) averaging intensity levels, (c) peak reading.

Dot recording and peak-reading bins

Since 1969 our film records have consisted of arrays of discrete dots, each dot indicating by its magnitude (both size and density change) the target intensity within a given bin. These dots are formed on the phosphor of a CRT, and photographed. Discrete values of dot magnitude are used. Because of tube-face flare, the number of discrete values must be kept small: 4 or 5 or 6. But it is because of tube-face flare that continuous variations are hazardous, so that we have been led to use discrete dots and discrete magnitudes.

In weather-radar technique, data are combined in groups of k independent data, to reduce uncertainty of target strength attributable to phase randomness. The standard deviation of this uncertainty is given, approximately at any rate, by

$$\sigma = (5.57 \text{ dB})/k^{\frac{1}{2}}$$

The procedure of data-combining affording the greatest reduction of uncertainty is the averaging of intensities. Another, almost as good, is to average intensity levels. Yet another, which we use because of its simplicity, is to take the maximum value among the k data. We use bins that are extensive only in range, and test the signal against a set of thresholds spaced uniformly in level, and report the highest threshold crossed.

REFERENCE: Marshall, J.S., 1971: Peak reading and thresholding in processing radar weather data. J. Appl. Meteor., 10, 1213-1233.

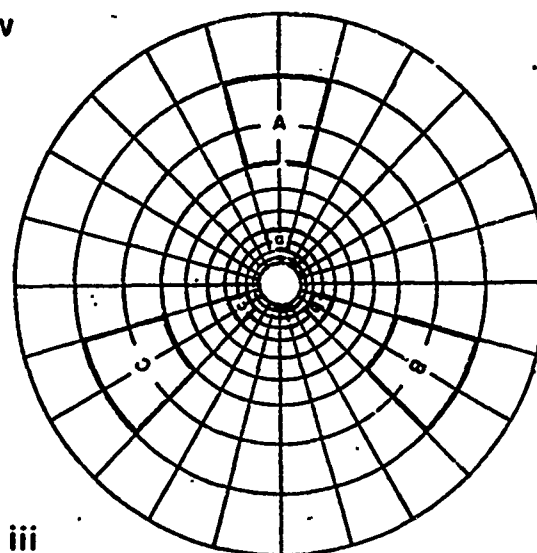
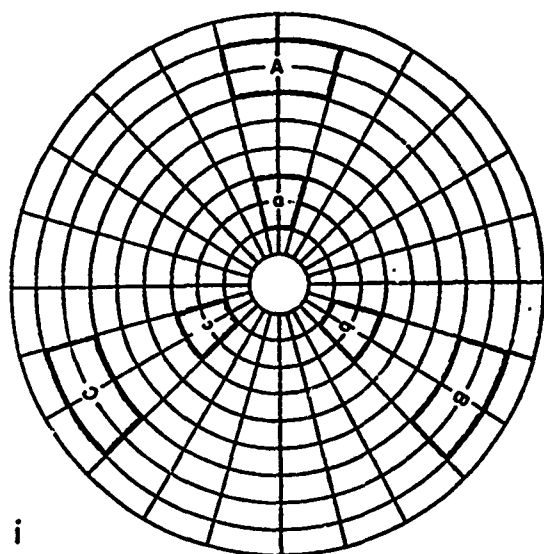
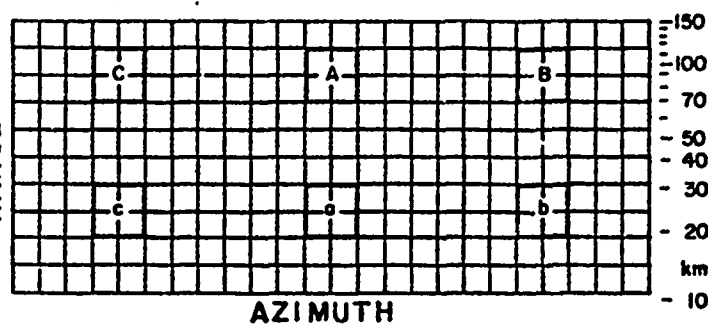
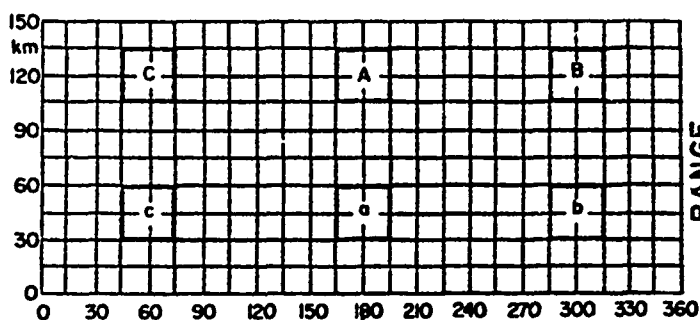


HPPI: Height Plus Plan Indicator (Hard Copy)

When a FASE antenna program is employed, a PPI display on a persistent-phosphor tube face is not much use, for one must be prepared to wait for the low-elevation part of the FASE cycle. An improvement can be effected by taking a Polaroid picture of the low-elevation PPI. We have improved on such Polaroids in four ways:

1. Thermofax with silver-salt paper is better than Polaroid in that it can be automated, and provides a bigger picture more cheaply.
2. A CAPPI map (to range 120 nmi, for heights between 5 kft and 10 kft) reduces ground echoes as compared with a low-elevation PPI.
3. A height ring around the map provides heights in 5-kft intervals, for the range interval 20 to 80 nmi.
4. The information is fed to the HPPI display at a slow rate over a period of 5 minutes, so that the hard copy can be generated at the far end of a telephone line. For a comprehensive remote display, this is an improvement over our old system, or any system that requires a few minutes to build up the comprehensive display, followed by another few minutes for the narrow-band transmission. This narrow-band use of HPPI hard copy has proved effect in a two-year operational test.

REFERENCE: Marshall, J.S. and E.H. Ballantyne, 1970: McGill Weather Radar: New Research and Remote Displays. Proceedings of 14th Radar Meteorology Conference, Tucson, Arizona, p407.



- (i) PPI, bin length constant, bin width proportional to range.
- (ii) B-scope, bins of PPI reproduced as squares of constant size.
- (iii) Modified PPI, bin length equal to bin width, proportional to range.
- (iv) AZLOR, bins of modified PPI reproduced as squares of constant size, so that ordinate scale is linear in log range. (AZLOR stands for AZimuth LOg Range.)

AZLOR (Azimuth/Log Range)

AZLOR in principle: The radial lines of a PPI provide an undistorted map. For the diagram in the lower left, we have assumed beamwidth 1° , one line of the PPI for each beamwidth, and have drawn every 15th line. We have further assumed the total range to be divided into 150 bins of uniform length, and have drawn circles at uniform intervals of 15 bins. Thus each enclosure of the figure contains 225 bins, each having shape the same as the enclosure, but area less by factor 225. If each bin were represented on the display by a dot (as in 1970) then at long range the dots would be too well spaced to merge into a half-tone pattern, while at short range they would overlap.

At the top left is a "B-scope" display, of range against azimuth. The keystone-shaped enclosures of the PPI (a,b,c,A,B,C) all become squares on the B-scope, whereas on the undistorted map of the PPI keystones a, b, c were narrower than the keystone height, and A, B, C were wider.

Bin width is proportional to range. In the diagram in the lower right, bin length has been made equal to width, so that all bins are the same shape, approximately square. Thus resolution in range is everywhere equal to resolution cross-range, which is a good arrangement. Now, however, dots representing bins would be very crowded toward the centre, their concentration varying inversely as range squared.

AZLOR equates bin length to bin width (as lower-right) but displays the dots in a uniform rectangular array (upper right) having coordinates of azimuth and \log_e (range), so that every bin and every enclosure of the lower-right diagram is reproduced on the display as a true square. The uniform spacing of dots means that the display can be read as a half-tone. While gross pattern elements are seriously distorted, the mapping is conformal, so that shape is preserved for small pattern elements.

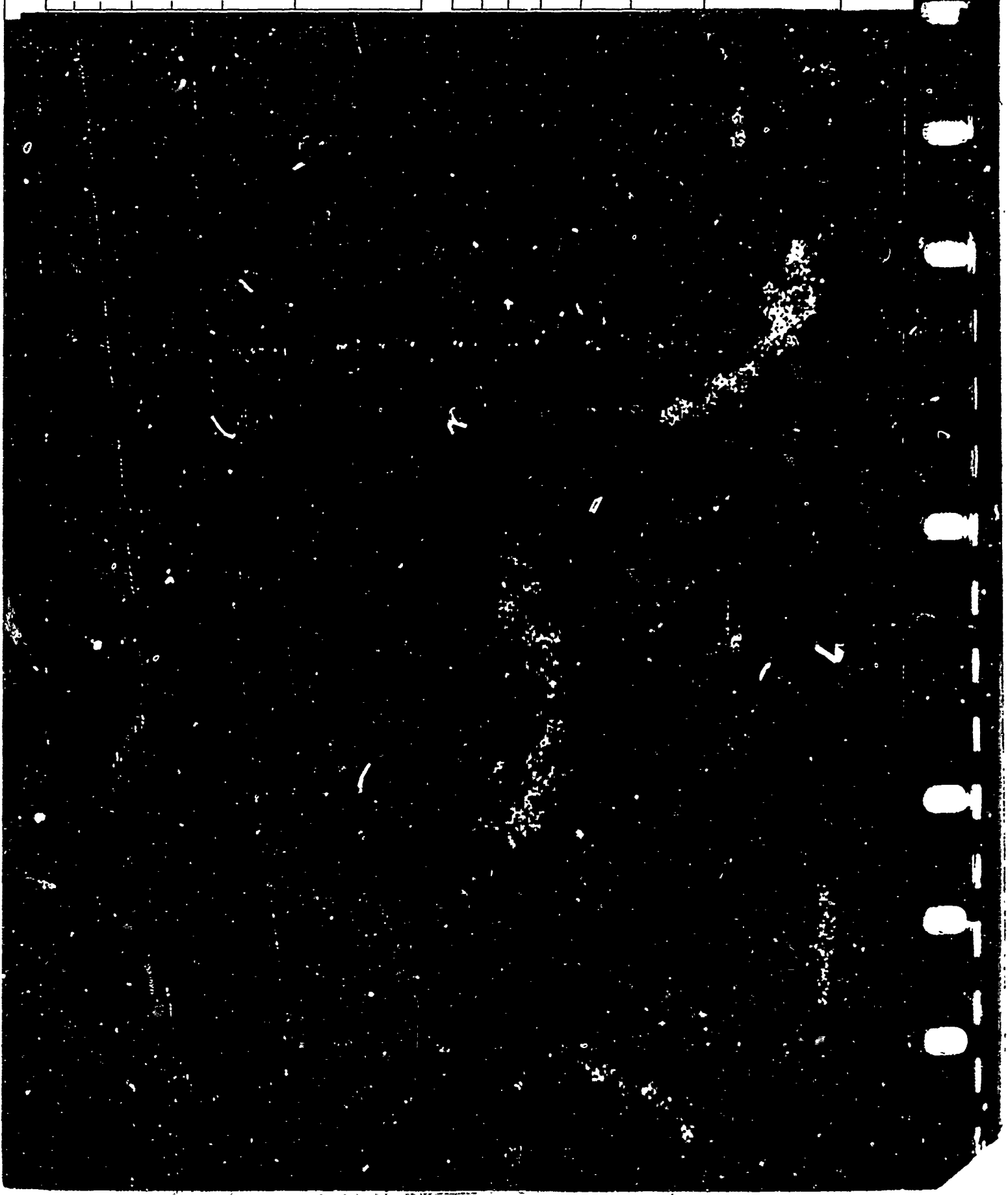
AZLOR complements PPI or CAPPI or HPPI: a person refers to the map-type display for gross features, transfers to AZLOR for detail. Useful conformity to the true pattern is found for regions as large as $\frac{r}{2} \times \frac{r}{2}$ at average range r .

RANGE (km)

200
150
100
50

25
200
150
100
50
25

112



18

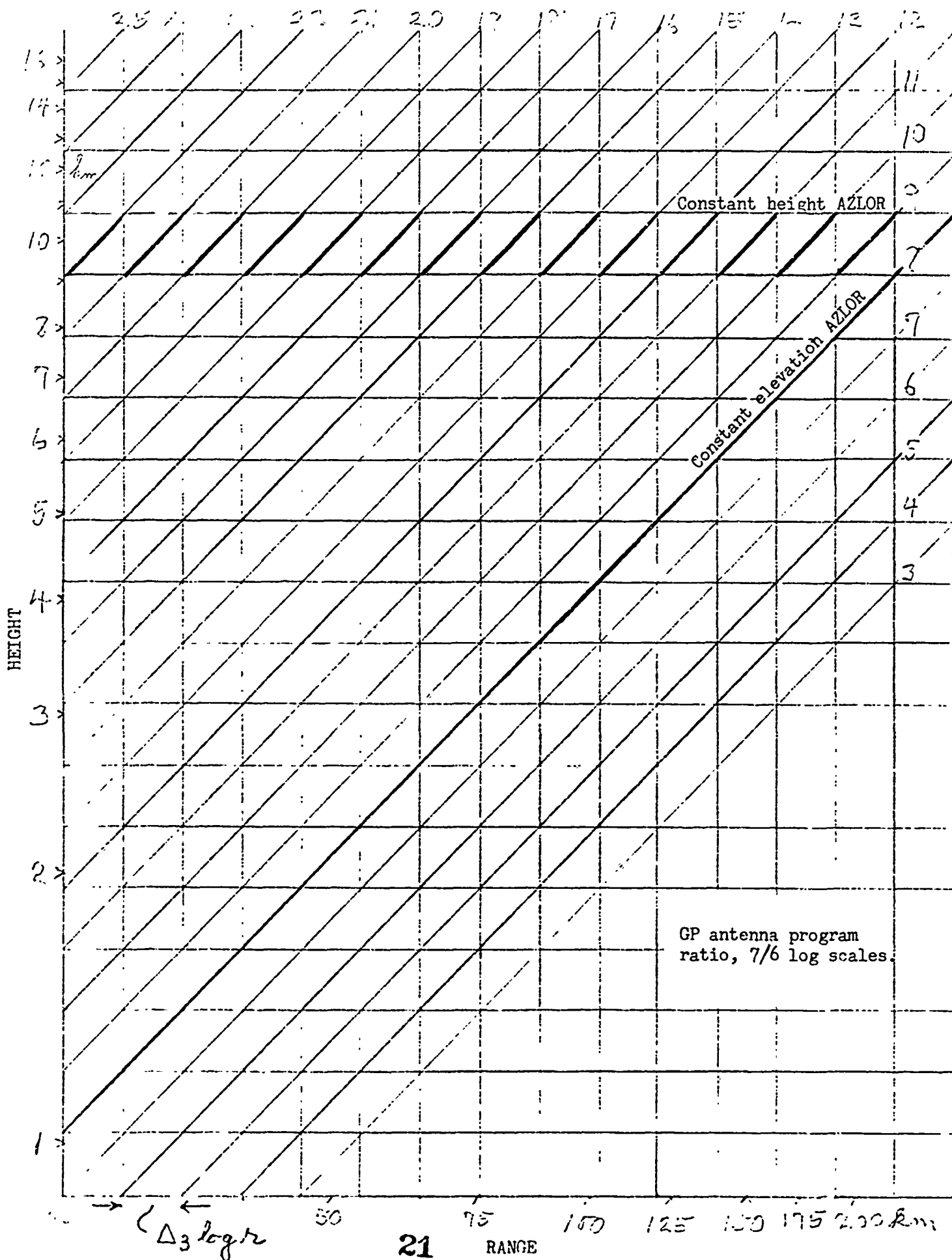
Display of Target Intensity

The AZLOR display has been built in duplicate, in lower and upper sections. In each section, the dots are displayed with four discrete magnitudes (brightness or density, and size). The dot magnitudes locate the target intensity level within intervals between thresholds: intervals of 20 dB in the upper section, intervals of 5 dB within the 20-dB intervals in the lower section. They thus function in a scale of four, the upper section providing the fours digit and the lower section the units digit, to identify 15 intervals of target intensity level, each of extent 5 dBz.

Fours	Units	10 log Z	Z mm ⁶ /m ³	R mm/h
	•			
	33			
	•	77	5.1	2402
•	32		$\times 10^7$	
	•	72	1.6	1170
	31			
	•	67	5.1	570
----	30		$\times 10^6$	
	•	62	1.6	277
	23			
	•	57	5.1	135
•	22		$\times 10^5$	
	•	52	1.6	66
	21			
	•	47	5.1	32
----	20		$\times 10^4$	
	•	42	1.6	15.6
	13			
	•	37	5.1	7.6
•	12		$\times 10^3$	
	•	32	1.6	3.7
	11			
	•	27	5.1	1.80
----	10		$\times 10^2$	
	•	22	1.6	0.87
	03			
	•	17	5.1	0.43
•	02		$\times 10$	
	•	12	1.6	0.21
	01			
	•	7	5.1	0.10
----	00			

- BACKGROUND -

Facing: Selected matching sections of earlier AZLOR, fours above and units below.



Constant-altitude AZLOR

Some of the virtues of a GP (geometric progression) antenna program become evident if the program is drawn against logarithmic scales of height and range. For constant-altitude AZLOR maps, slices equal in $\Delta \log r$ are selected from the sequence of constant-elevation maps. The spacing of the AZLOR dots ($\Delta_2 r$) has been made equal to Δs , the spacing between successive range lines, so that

$$\frac{\Delta_2 r}{r} = \frac{\Delta s}{r} = \frac{2\pi}{680} = \frac{1}{95.5}$$

$$\Delta_2 r = r/95.5$$

$$\Delta_2 \log r = 0.4343/95.5 = 0.00452$$

Then the GP factor in the antenna program (approximately 7/6) has been so chosen that $\Delta_3 \log r$ is an integral multiple of $\Delta_2 \log r$:

$$\Delta_3 \log r = 15 \Delta_2 \log r = 0.678$$

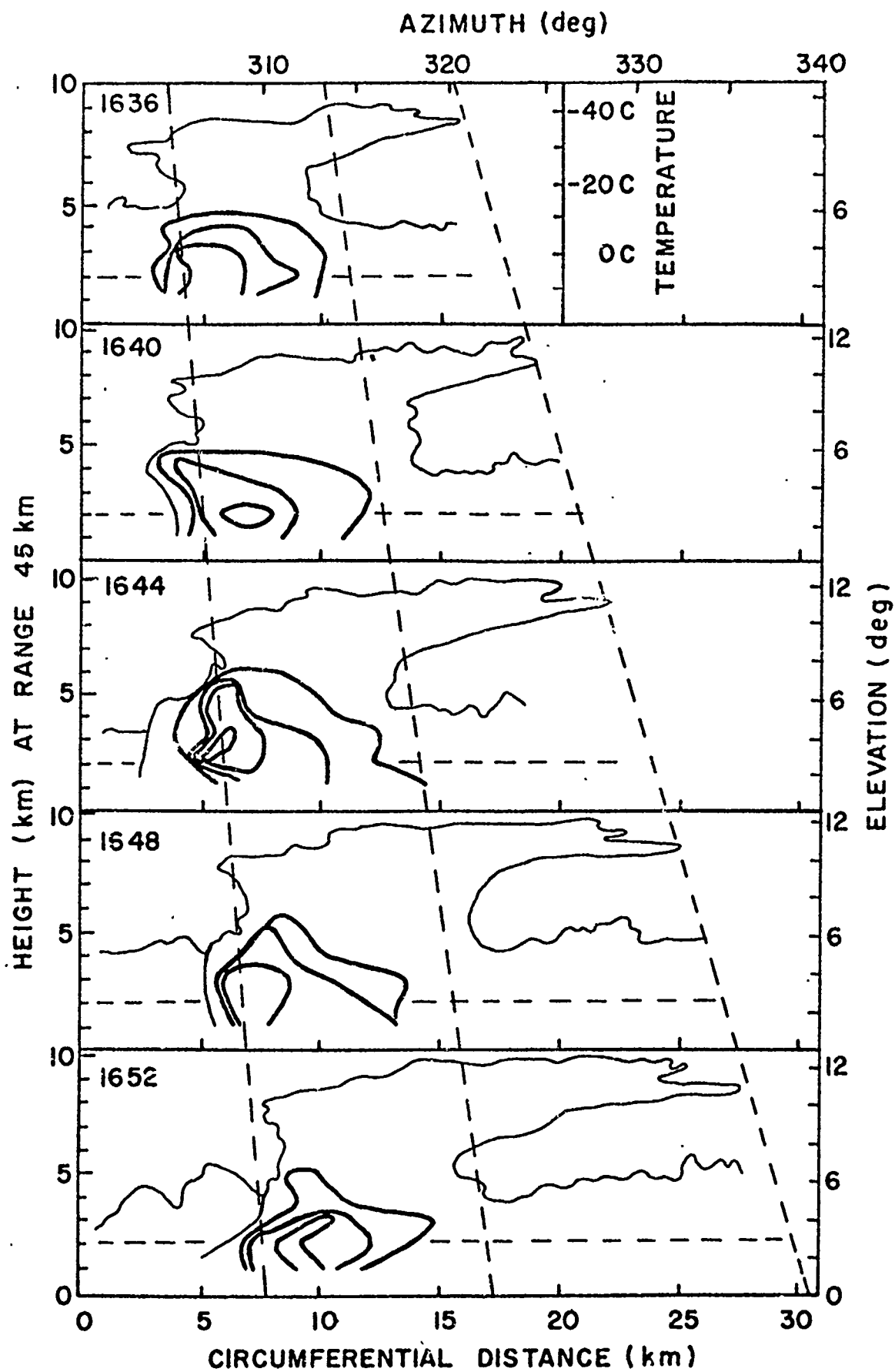
A simple reorganization of the " Δ_3 " elements would permit an output of about 20 constant-altitude AZLOR maps in place of the constant-elevation maps that come naturally. A related reorganization of these " Δ_3 " elements would array them in constant-range (within the factor 7/6) columns.

Some years ago we aspired to achieve this data processing on magnetic discs, and to record the reorganized data on magnetic tape, one height for each track on the tape. We foresaw the tape record as highly amenable to further specific processing, using the same magnetic discs. These aspirations have not been achieved.

HARPI (Height Azimuth Range Position Indicator)

We went to a 4- μ sec pulse with two aims: to use the pulse uncompressed for maximum sensitivity, and compressed by factor 13 for maximum resolution. The compression factor is not very different from 15, the number of dots in a GP element. Thus we could obtain about the same k by using the GP element as bin length and the uncompressed pulse and by using the dot-spacing as bin length and the compressed pulse. The processed data for the full five-minute cycle can be displayed on one HARPI frame.

In this version of HARPI, the scales of height and range become logarithmic. The lowest of the 18 strips is for range 15 to $\frac{7}{6} \times 15 = 17.5$ km. The next goes from 17.5 to $\frac{7}{6} \times 17.5 = 20.5$ km, and so forth, so that the topmost strip is for range interval 183 to 250 km. For the lowest strip, the heights range from 1.0 to 9.0 km, while for the topmost strip the height range is from 4.0 to 43.3 km. The hope is to have the same height scale at all ranges, say 2.0 to 18 km.



Cloud Photogrammetry

For just a few hours each summer, it is possible to obtain good stereo cloud pictures. The following is the abstract of a manuscript being (re)submitted for journal consideration.

Showers observed by stereo cameras and radar

R.W. Shaw and J.S. Marshall

Department of Meteorology, McGill University

Panoramic (rotating-lens) cameras with fields $140^{\circ} \times 55^{\circ}$ have been used for stereoscopic photography of clouds, in conjunction with 10-cm radar observations. The photographs are linear in the parameters used in photogrammetry: azimuth and the tangent of the angle of elevation.

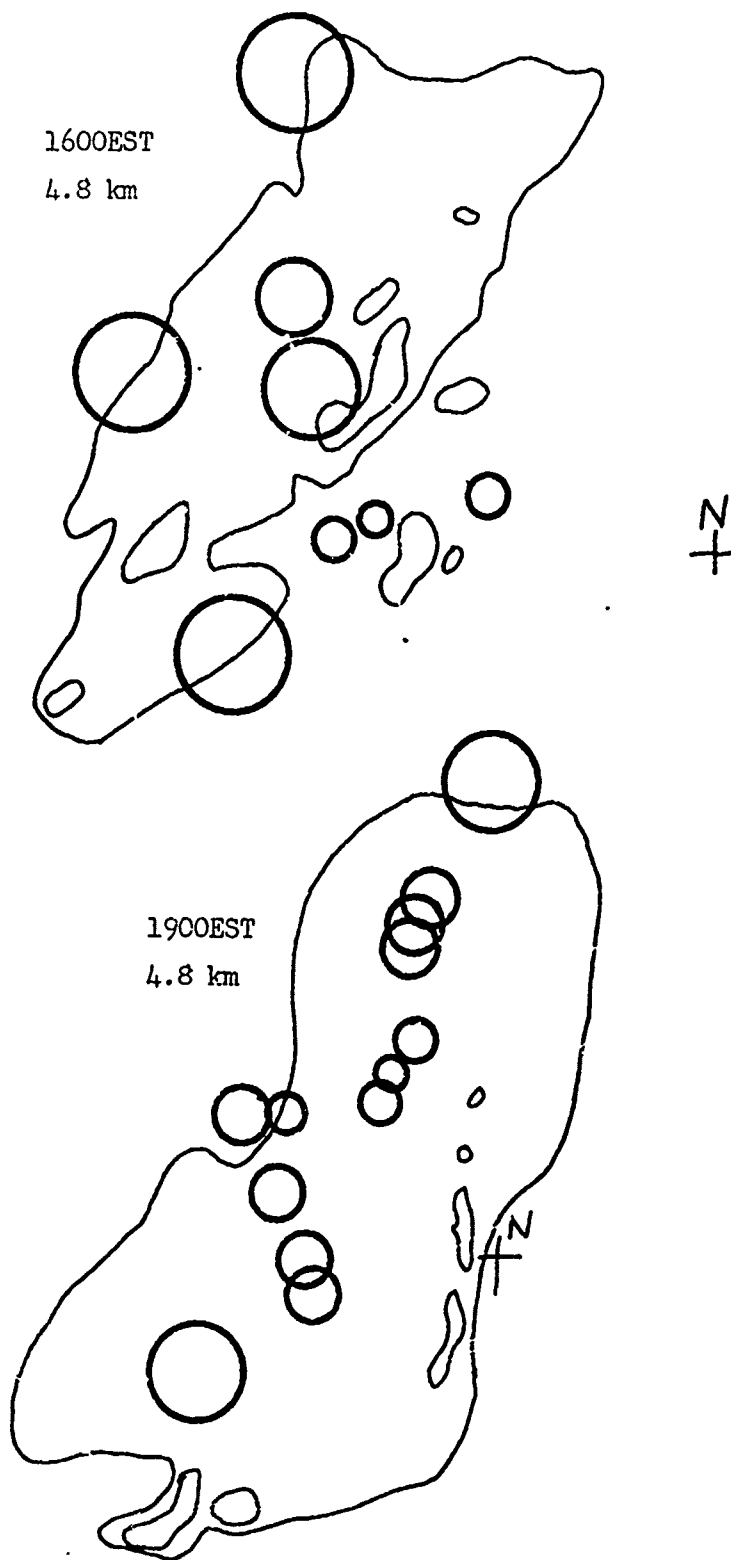
On 26 July 1969, three isolated showers moved in the direction (the same at all heights) of the wind. Large and largely irregular changes were noted in the four-minute interval between observations, but strong gradients in the precipitation observed by radar, and thin cloud envelopes (from precipitation to cloud boundary), were frequently observed, and tended to lie in the general direction of the wind and the late afternoon sun. All three shower clouds had heights of 10 km; in two the precipitation extended almost to the top of the cloud, but in the third, for which directions of sun and wind were identical, the precipitation top was at from 5 to 7 km.

Motion could be interpreted in terms of a mixture ranging from almost wholly sub-cloud air on the side generally toward sun and wind to almost wholly upper-level air for the anvil tip and detached anvils. This indicates that sub-cloud air from the sunny side of the shower was brought into the cloud via an updraught near the upwind end of the shower, and that it then mixed with ambient air and moved downwind relative to the undiluted core of the updraught.

Facing: 26 July 1969

Light outline: Visual and photographic cloud.

Heavy outline: Radar isopleths, in steps of 10 dBZ.



Lightning locations for the storm of July 25th, 1969.

Radio Lightning Location

Lightning flashes may be located by observing sferics using three spaced, loop aerial, direction finders. Positions of events found in this way have been plotted on radar maps of precipitation. The conclusions from the results which are neither as accurate nor as numerous as we would like are that the discharges tend to be located close to but not inside convective cells containing the intense precipitation.

The experiment is being continued with considerably improved equipment.

REFERENCE: Austin, G.L. and E.J. Stansbury, 1971: The location of lightning and its relation to precipitation detected by radar.

J. Atmosph. Terr. Phys. 33, 841-844.

ADA CALIBRATION A(dB)

20
15
0
5

Example of slant PPI, including ADA display.
Elevation is 8.5° and total range is 55 mi.

Microwave Attenuation

Based on empirical relations among rainfall rate, reflectivity, and attenuation, ADA is an instrument used in connection with our radar which provides a display of the attenuation due to rain at 10 GHz over the radar line of sight. The attenuation is indicated as a deflection trace around the perimeter of an otherwise conventional PPI. In the example shown on the facing page, the strong echoes toward the east are seen to cause attenuation in excess of 10 dB (at 10 GHz) over an azimuth extent of about 5°.

The deflection is produced by an analog circuit which evaluates an integral of reflectivity over range, of the form

$$A = \int K Z^{\alpha} dr$$

where K and α are empirical constants chosen for 10 GHz, and the limits of integration are 5 mi and 55 mi. The inner cutoff at 5 mi eliminates spurious effects due to ground clutter.

From a long sequence of such pictures, statistics are compiled on the frequency of occurrence of attenuation as a function of elevation and bearing, and the distribution of azimuth extents of attenuating regions.

Results from three summers of operation show that the frequency of occurrence diminishes rapidly as the elevation increases from horizontal to 10°, and is essentially constant from there on to 20°. 5 dB is exceeded 10 hr/yr at 3° elevation, 4 hr/yr at 10°, and 3.5 hr/yr at 20°. At all elevations 10 dB is exceeded about one-fifth as frequently as 5 dB.

The azimuth extents of attenuating regions vary from 1°, the narrowest extent measurable, to values exceeding 60°. At low elevations, the distributions of azimuth extent are strongly peaked at the narrow end. With increasing elevation the distributions flatten. The average azimuth extent of a 5-dB region increases approximately linearly from 10° at an elevation of 3° to 30° at an elevation of 20°. For all elevations the average 10-dB extents are about half the 5-dB extents.

The average duration of a 5-dB event decreases from about 30 min at near-horizontal paths to less than 10 min at an elevation of 20°. For all elevations the average duration of a 10-dB event is about two-thirds that of the 5-dB event.

Papers scheduled for June publication in Radio Science:

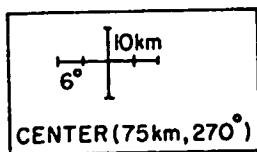
ADA: An instrument for measuring attenuation due to rain over slant paths,
by I.I. Zawadzki and R.R. Rogers.

Radar-derived statistics on slant-path attenuation at 10 GHz, by R.R. Rogers.

JULY 14, 1971

(km)

5.7 + + + + + + + + + + + + +



4.8 + + + + + + + + + + + + +

4.2 + + + + + + + + + + + + +

3.6 + + + + + + + + + + + + +

3.1 + + + + + + + + + + + + +

2.8 + + + + + + + + + + + + +

2.4 + + + + + + + + + + + + +

2.0 + + + + + + + + + + + + +

1.8 + + + + + + + + + + + + +

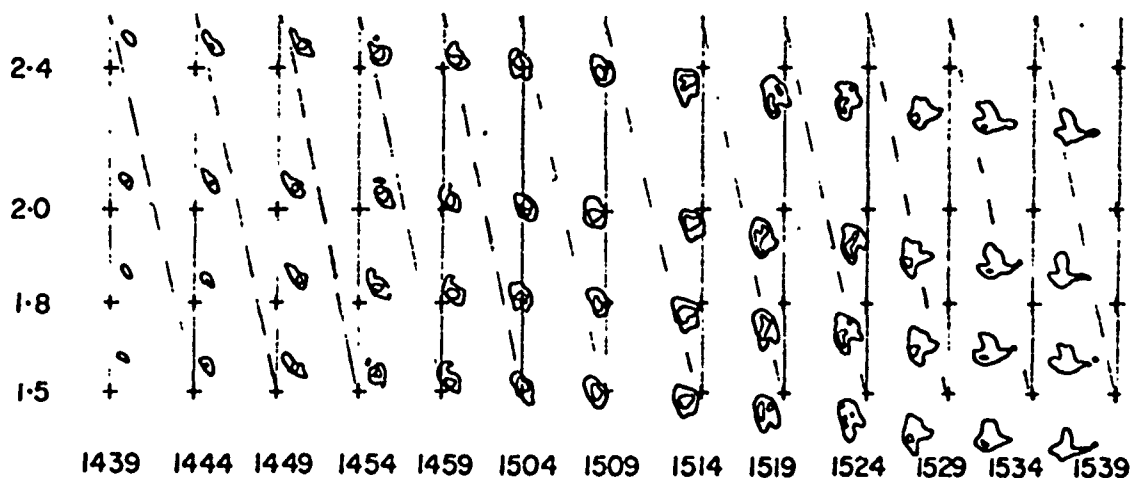
1.5 + + + + + + + + + + + + +

1439 1444 1449 1454 1459 1504 1509 1514 1519 1524 1529 1534 1539

A complete set of horizontal slices through
a shower at the heights and times shown.

Interpolation and extrapolation techniques for radar precipitation patterns

The FPS-18 radar as used at McGill takes 5 minutes to record the three dimensional structure of precipitation patterns. Specifically for use in comparison with microwave-link attenuation, it was desired to have precipitation patterns close to the surface with a time resolution of about one minute. Shorter intervals are not justified, when radar resolution is taken into account. Procedures have been established which enable this coarse sampling time to be improved by interpolation of patterns from an earlier time but higher altitude. Arrays of data like the one shown opposite allow pattern matching techniques to give an 'effective pattern fallspeed' and the precipitation pattern to be extrapolated to the ground with a time resolution improved by a factor of about five. The sawtooth line (below) gives the expanded time scale for the 13 cycles of the figure.



Achievements in 1971-2

1. First high-resolution AZLOR display developed and put to use. Film record indicates intensity by two digits of scale of four on conformal maps.
2. First use of pulse compression in weather radar provides high resolution without undue sensitivity loss.
3. Long pulse without compression provides maximum sensitivity, recorded on new HARPI display.
4. Most severe storms from summer AZLOR records analyzed, primarily to provide microwave-attenuation statistics.
5. Storm for which cloud photographs were available analyzed to relate precipitation seen by radar to cloud seen by camera.
6. Precipitation measurements by radar extrapolated to surface (new technique) and compared with raingauges.
7. Ten thousand lightning flashes radio-located (as to direction), and locations compared with radar maps of precipitation.
8. One-hour-forecast possibilities explored on PPHI records.
9. Paper published on Peak Reading as signal-processing technique.
10. Report published on interrelationship of showers and contiguous rain.
11. A thesis was submitted on autocorrelation analysis of radar maps of rain.
12. Fortnightly seminars for critical examination of dynamics and microphysics of severe storms.
13. Paper accepted on measurement of snowfall by (CPS-9) radar.
14. Paper submitted on showers observed by camera and radar.

Continuing and Future Projects

1. MARSHALL
1972
Report and paper to be prepared on five-dimensional high-resolution weather radar system incorporating the various McGill technical developments.
2. DRUFUCA
AUSTIN
BALLANTYNE
MARSHALL
1972
New techniques of electronic calibration of weather radar to be developed.
3. BALLANTYNE
STAFF
1972
Minor improvements in AZLOR display.
4. BALLANTYNE
STAFF
1973
Improved version of AZLOR display to be built.
5. BALLANTYNE
MARSHALL
AUSTIN
DRUFUCA
1974
Improved amplifier circuitry to be developed, incorporating as much as possible of logarithmic thresholds, sensitivity time control (including peak-reading correction). It should be possible to use full sensitivity of system at all ranges.
6. STANSBURY
BALLANTYNE
STAFF
1972 or 3
Radio location of lightning flashes to be extended again to triangulation from 2 or 3 stations.
7. MARSHALL
DRUFUCA
STUDENT
1972-3
5D census of summer storms at Montreal, with relevance to physical meteorology and application to microwave attenuation.
8. DRUFUCA
STUDENT
1972 and 3
Attenuation over microwave link: calculations from radar record to be compared with actual (Bell-North n Research) link.
9. MARSHALL
AUSTIN
DRUFUCA
STUDENTS
1972 et seq
Thunderstorms selected from summer records to be analyzed for life histories (storm dynamics) and for storm-by-storm approach to attenuation statistics.
10. AUSTIN
STUDENT
1972 et seq
Stereo cloud photographs to be recorded when weather permits, and analyzed to supplement (9).
11. DRUFUCA
STUDENT
1972 et seq
Rainfall and snowfall rates and amounts to be determined by radar, checked by gauges.
12. STANSBURY
STUDENT
1972 et seq
Radio location of lightning flashes to be related to precipitation pattern by radar.
13. AUSTIN
STUDENT
1972 et seq
One-hour-forecast techniques to be developed, introducing storm-dynamic processes. (In summer, for example, cells do not persist but showers do.)

Papers in Proceedings of 14th Radar Meteorology Conference

1. Comparison of Radar with Network Gauges
Desautels, G. and K.L.S. Gunn, p 239
2. Problems of Snowfall Measurement by Radar
Carlson, Paul E., p 245
3. Motion of Radar Echoes within Cloud Envelope
Shaw, R.W., p 297
4. Finding the position of lightning flashes
Austin, G.L., p 313
5. Showers and Continuous Precipitation
Zwack, P. and C. Anderson, p 335
6. McGill Weather Radar: New Research and Remote Displays
Marshall, J.S. and E.H. Ballantyne, p 407
7. Radar Weather Performance Enhanced by Pulse Compression
Fetter, R.W., p 413
8. Autocorrelation of Weather Patterns by an Incoherent Optical Method
Zawadzki, I.I., p 421
9. Decorrelation Time of Weather Radar Signals
Reid, J.D., p 419

Papers directly dependent on FPS-18

- Austin, G.L. and R.W. Fetter, 1972: Pulse compression for meteorological radars. Stormy Weather Group Scientific Report MW-70.
- Austin, G.L. and E.J. Stansbury, 1971: The location of lightning flashes. J. Atmosph. Terr. Phys., Vol. 33, p841.
- English, Marianne, Charles Warner and W. Hitschfeld, 1972: Observations and theory of a hail storm. Journal de Recherches Atmospheriques for the Henri Dessens Memorial issue (submitted).
- Marshall, J.S., 1971: Peak reading and thresholding in processing radar weather data. J. Appl. Meteor., Vol. 10, 17 pp.
- Marshall, J.S. and R.W. Shaw, 1972: Showers observed by stereo cameras and radar. (Submitted to Monthly Weather Review.)
- Rogers, R.R., 1972: Radar-derived statistics on slant-path attenuation at 10 GHz. Scheduled for June publication in Radio Science.
- Zawadzki, I.I. and E.H. Ballantyne, 1970: HARPI - a new weather radar display. Q.J. Roy. Met. Soc., 96, 144-5.
- Zawadzki, I.I. and R.R. Rogers, 1972: ADA: An instrument for measuring attenuation due to rain over slant paths. Scheduled for June publication in Radio Science.
- Zwack, Peter P., 1971: Showers and continuous precipitation: 25 July 1969. Stormy Weather Group Scientific Report MW-65.

Also papers from the 14th Radar Weather Conference, 1970.